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Hotspots and the Evolution of the Mantle

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Abstract

Trace element patterns show that continental and ocean island basalts are complementary to mid-ocean ridge basalts. The relative sizes of the two source regions can be estimated from enrichment/depletion patterns. Their combined volume, computed from estimates of whole mantle abundances, occupies the entire upper mantle. The source regions appear to be the result of an early differentiation of the mantle. The MORB source evolved from the melt fraction which lost its late stage enriched fluids to the overlying plume source. The MORB source is primarily garnet and clinopyroxene, consistent with it being an eclogite cumulate.

Hotspots, or plumes, have not yet been fitted satisfactorily into either the tectonic or geochemical framework for the evolution of the mantle. From the point of view of mantle processes and the chemical evolution of the mantle the alkali volcanism associated with hotspots is a very important process even if the abundance of such rocks is small compared to the volume of abyssal tholeiites (1). The processes of creation and subduction of oceanic crust and lithosphere clearly account for most of the mass transport into and out of the upper mantle and the study of mid-ocean ridge basalts (MORB) has placed important constraints on the part of the mantle that is providing these magmas. Trace element and isotopic considerations show, however, that the source region for MORB cannot be representative of the average composition of the mantle nor can it have existed as a separate entity with its present characteristics for the full age of the Earth. The composition, location and volume of the source region, which we designate MORBS, are still uncertain. It appears to be homogeneous, global in extent, and to be the result of a previous differentiation or fractionation process that depleted it, relative to other source regions, in most of the incompatible elements. On the other hand, it is clearly not lacking in a basaltic component. The continental crust is complementary to MORB in both trace elements and isotopic ratios (2,3). Formation of the continents has presumably been at least partially responsible for the depletion of the so-called oceanic mantle. If the continental crust is the only enriched reservoir, then mass balance calculations indicate that only about 30% of the mantle has been processed, the rest remaining undifferentiated and primordial (3,4). A large primitive reservoir would be difficult to reconcile with other evidence regarding the early thermal evolution of planetary interiors. There is, however, evidence for an additional enriched reservoir in the mantle. Magmas from continental interiors, rift zones, oceanic islands, anomalous ridge segments and island arcs, mantle xenoliths from kimberlites and alkali basalts, and kimberlites themselves, all indicate the presence of a reservoir with trace element patterns complementary to MORB. This reservoir apparently is also global and can provide magmas to a variety of tectonic environments including all types of plate boundaries as well as plate interiors. These magmas, of which alkali basalts are one example, are not nearly as voluminous as MORB but they indicate the presence of an enriched region or layer which may be substantial compared to the continental crust. We shall designate this as the hotspot or plume reservoir, or simply PLUME (5), and assume that it is the source of alkali basalts, nephelinites, melilitites, basanites, kimberlites and continental tholeiites which it provides by varying degrees of partial melting (6,7). One of the diagnostic signatures of these basalts is the rare-Earth element (REE) pattern which implies a source enriched by about 10 in LREE and 3 in the HREE, relative to chondrites (6,7,8).

PLUME basalts also have high ratios of Rb/Sr, Rb/K, Ba/K, Nd/Sm, Ba/Nd, Ba/Sr, Nb/Zr, $^{87}Sr/^{86}Sr$, and $^{144}Nd/^{143}Nd$, and high concentrations of H_2O, CO_2, K, Rb, Sr, Ba, La, Nd, Th, and U relative to MORBS. These characteristics are shared by continental and ocean island basalts and are also evident, albeit diluted, in back-arc basins, island arcs, and transitional or anomalous ridge tholeiites. Other characteristics which may be common but which have been studied in only a few hotspot locations are high abundances of primordial rare gases, Cl, F and Br (9). The process that led to the enrichment of PLUME will have depleted other, presumably deeper, regions of the mantle.

Plume basalts

The continental crust is extremely enriched in the incompatible trace and minor elements. Continental tholeiites, basanites, nephelenites, alkali basalts, kimberlites and basalts from oceanic islands are also enriched. The complement to the depleted mid-ocean ridge source region is, therefore, much more voluminous than just the continental crust. The trace element and isotopic affinities of these magmas, regardless of their tectonic setting, suggests that they are all derived from a similar source region. This reservoir, PLUME, has previously been referred to as continental mantle, the enriched source region or primitive mantle. Its location is uncertain. Proposals include the uppermost (6,10) and lowermost (11) mantle. In trace element ratios such as Ba/Nd, Nd/Sm, Ba/Sr, Ba/K and Rb/K there is a progressive increase from ocean island and island arc basalts, basalts from anomalous ridge segments, continental tholeiites, alkali basalts to kimberlites. Mid-ocean ridge basalts have much lower ratios and tholeiites from back-arc basins are generally slightly higher than MORB. Trace element concentrations vary systematically through the compositional spectrum olivine melilitite, olivine nephelinite, basanite, alkali olivine basalt, olivine basalt and olivine tholeiite and can be explained by varying degrees of partial melting ranging from 4 to 25% from a common source region which is enriched in the strongly incompatible elements (Ba, Sr, Th, U, LREE) by ∿10x chondritic and in the moderately incompatible elements (Ti, Zr, Hf, Y, HREE) by a factor of about 3 less (6-8). Mid-ocean ridge basalts are derived from a very different source which is depleted in the large-ion lithophile (LIL) elements. The complementary nature of the two source regions is possibly due to the migration of a melt or fluid with incompatible element concentrations similar to kimberlite. This fluid depletes the MORB source region and enriches the complementary mantle reservoir. The upper mantle low-velocity zone (LVZ) is the most likely repository of these trace element enriched fluids and, therefore, a likely source region for the enriched magmas which are characteristic of the plume or hotspot source. Kimberlites come from depths as great as 220 km, consistent with an origin near the bottom of the LVZ. The xenoliths in kimberlites and alkali basalts represent mantle fragments from various shallower depths and also generally exhibit enrichment of the type inferred for the plume source region. Evidence for uppermantle metasomatism comes from a variety of sources including mantle derived xenoliths, the trace element enrichment of granular nodules which have previously lost a basaltic component and isotopic studies (12). The complementary nature of continental and oceanic tholeiites is illustrated in the center part of Figure 1. Alkalii basalts, nephelinites, melilitites and basanites have similar but more enriched patterns, consistent with their derivation from the same source region by smaller degees of partial melting. Continental and abyssal tholeiites exhibit near perfect reflection symmetry about a plane corresponding to a 6 to 7 fold enrichment over average mantle concentrations.

Continental and ocean island basalts are relatively depleted in those elements that are retained by garnet and clinopyroxene. The reverse is the case for abyssal tholeiites. Since garnet and cpx are reduced or eliminated during the large amounts of partial melting required for the formation of tholeiites, the inverse ga-cpx pattern of plume basalts must be related to a previous episode of basalt extraction or invasion by a fluid that was in equilibrium with a ga-cpx assemblage.

The origin of island arc basalts is still controversial but they have PLUME affinities in such trace element ratios as Rb/K, Rb/Sr, Ba/K, Ba/Sr and Ba/Nd. These ratios are closer to ocean island basalts, alkali basalts and continental flood basalts than they are to mid-ocean ridge basalts. Back-arc basin basalts are intermediate to MORB and hotspot magmas, suggesting a mixture from a deeper MORB source and an overlying enriched source region. Ocean island tholeiites also appear to be mixtures both in trace element and isotopic ratios (2). The fact that both MORB and basalts with continental affinities are available at ridge enrivonments, island arcs, oceanic islands and well developed continental rifts suggests a compositionally stratified mantle. The order of appearance of these basalt types is consistent with the shallower layer being enriched in the incompatible trace elements. In a stratified mantle the deeper layer should be denser and, therefore, more garnet rich. The ratio of concentrations in MORB to those in continental tholeiites indicates that the MORB source region, although depleted in most of the incompatible trace elements, has selectively retained those that are most comfortable in the garnet and clinopyroxene lattices.

The composition of the two source regions

The concentrations of some key incompatible trace elements in various magma types is given in Figure 1. Continental tholeiites, alkali basalts, kimberlites and the continental crust have similar enrichment patterns. Note that the enriched magmas are most enriched in K, Rb, Ba, La and U. These are the elements that are most discriminated against by the major mantle minerals, olivine, orthopyroxene, clinopyroxene and garnet, i.e., they have the lowest mineral/melt partition coefficients. The other elements are also strongly rejected by olivine and orthopyroxene, having partition coefficients of less than 0.03 for these minerals (6). On the other hand, garnet and clinopyroxene have partition coefficients greater than about 0.1 for Y, Nd, Sm, Sr, and Yb. These are the least enriched elements in the magmas with continental affinities and the most enriched in MORB. It appears that garnet and clinopyroxene are abundant minerals in MORBS, and that the fluid which enriched PLUME was previously in equilibrium with a ga-cpx rich reservoir.

The high concentration of Y and Yb in MORBS relative to other elements and relative to concentrations in basalts from PLUME, the enriched source region, is particularly significant. These elements have crystal/melt partition coefficients greater than unity for garnet. This is two orders of magnitude greater than would be appropriate for an olivine-orthopyroxene rich assemblage. Mass balance calculations suggest that most of the terrestrial inventory of Y and Yb may be in the

MORB source region. This can only be accomplished if garnet is a dominant phase and if most or all of the mantle has experienced differentiation.

The relative volumes of the two source regions can be inferred from Figure 1 if it is assumed that they, plus the continental crust, give an undifferentiated terrestrial pattern for the very incompatible elements. Using 0.56% for the mass of continental crust relative to the mantle (3) we compute that the mass of MORB must exceed the tholeiitic fraction of PLUME by a factor of 12 to 15. Continental tholeiites represent about 20% melting of a peridotitic source region (6) and MORB must be mixed with about 15% olivine to recover the composition of its parent magma (13,14). The residual crystals in both cases are assumed to be depleted because of their very low partition coefficients (6,8). The MORB source region is, therefore, at least 2.8 to 3.5 times the mass of PLUME and the relative enrichment of the combined source regions is about 3.3 to 3.8. Note that MORBS is depleted only in a relative sense. Compared to average mantle abundances it is enriched. This suggests that MORBS plus PLUME are complementary to the remainder of the mantle from which they have presumably been removed by partial melting. The enrichment factor implies a residual mantle about 2-1/2 times the size of the combined reservoirs.

By assuming that the very incompatible elements have been entirely fractionated into the two source regions it is possible to estimate their total volume. For example, if La is depleted in the lower mantle the combined source regions represent 26 to 30% of the mantle. This corresponds to a thickness of 560 to 640 km in the upper mantle, or a region extending upwards from the 670 km discontinuity to a depth of 27 to 110 km. If we take the transition region, 220-670 km, to be the depleted source region (20), then PLUME is 130-160 km thick, about the average thickness of the low-velocity zone (LVZ).

A similar calculation for the other strongly incompatible elements (K, Rb, Ba, U) gives a range of 21-38% for MORBS plus PLUME. These are upper bounds since it has been assumed that the whole mantle has been processed and depleted. This, however, is a good approximation if olivine and orthopyroxene are the main residual phases. It is significant that the above estimates of the relative and absolute sizes of the principal mantle reservoirs correspond to the main subdivisions of the upper mantle, the LVZ and the transition region. The 670 km depth corresponds to a major seismic discontinuity and the maximum depth of earthquakes.

Other elements can be used to estimate the sizes of the individual reservoirs. The partition coefficients of Yb and Y are such that they strongly prefer the garnet structure (15). Both are enriched in MORB relative to PLUME, suggesting a higher portion of garnet in the former. If the entire mantle complement of Y and Yb reside in MORBS, then this would represent 14-17% of the mantle or an upper mantle equivalent thickness of 300 to 364 km. Sc is partitioned into garnet and clinopyroxene by a factor of 8 relative to olivine and orthopyroxene. Using this ratio of enrichment for the MORB source relative to the rest of the mantle it would constitute 26% of the mantle.

K, Rb, Ba, La and U have the highest relative concentrations in PLUME. These are the elements with the lowest partition coefficients for the major mantle minerals and those that are most likely to be concentrated into PLUME by melts or metasomatic fluids. The PLUME abundances of these elements can account for the entire mantle inventory if PLUME is 9 to 19% of the mantle. These are again upper bounds.

Using the above estimates of the relative sizes of the two source regions and Ganapathy and Anders (37) values for terrestrial abundances, we can now estimate the total abundances of the trace elements in the various reservoirs. The continental crust contains more than 26% of the mantle plus crust inventory of K, Rb, and Ba and less than 8% of Sr, Y, Zr, Nb, Sm, Yb, and Hf. The "depleted" MORB source contains more than 50% of the Earth's inventory of Y, Zr, Nd, Sm, Yb, Hf and Th and more than 20% of Nb, La and U. The PLUME source region, although generating highly enriched magmas contains only about 10 to 20% of the Earth's K, Rb, Sr, Nd, Sm, Yb, Th, and U. It is the primary repository for Ba and La and has small total abundances of Y, Zr, Nb, and Hf (less than 7%). The crust and the two upper mantle reservoirs account for about 75% of the heat production from K, Th, and U. Therefore, 25% of the Earth's heat flow comes from below 670 km. About 40% is due to MORBS. The continental crust and PLUME each contribute about 18%.

This distribution of heat sources affects the style of convection in the two reservoirs. Assumming PLUME to be the shallower reservoir it is primarily heated from below and will therefore be characterized by narrow ascending plumes. MORBS is primarily heated from within and will be characterized by broader ascending regions and narrow descending jets or "slabs".

The mineralogy of the two source regions

Assuming that the two source regions are related, an apparent partition coefficient can be determined by forming the ratio of the concentrations in MORB to those in continental tholeiites (CFB). This is shown in Figure 2 along with solid/melt partition coefficients for garnet, clinopyroxene, orthopyroxene and olivine. Tholeiites are used in this comparison since they are products of large degrees of partial melting. They will, therefore, have the trace element pattern of their source and a relatively uniform enrichment. The ratio of the concentrations in the two reservoirs can be explained if the MORB source is composed mainly of garnet and clinopyroxene and PLUME has been enriched with fluids that were in equilibrium with this layer and therefore depleted in such elements as Zr, Nb, Y, Yb, and Hf.

Note that MORB is enriched with respect to continental tholeiites in Y and Zr and only slightly depleted in Hf and Yb. Both MORB and continental tholeiites represent rather large degrees of partial melting of their respective source region. A garnet peridotite would be expected to lose most of its garnet and clinopyroxene under these circumstances. The above results indicate that primary garnet must be a minor mineral in PLUME but a major component of the MORB source. MORB is depleted in the most incompatible elements, such as K, Rb, Ba, and U but not as much as would be expected if it were composed entirely of residual crystals. This suggests that MORBS evolved from a melt, presumably the result of an early differentation event, and consists of a mixture of this crystallized melt with excess garnet which has settled into it during crystallization. The upper part of the mantle would consist of lighter residual crystals and late stage fluids which impart an inverse garnet signature to this region.

This sequence of events, based on trace elements, is precisely what O'Hara et al. (14) proposed on the basis of petrological and major element considerations. They concluded that the ultimate parent magma for ocean island tholeiites had extracted from it an early eclogite cumulate. The remaining magma evolved to ocean island tholeiite by olivine fractionation. Eclogite cumulates appear to have the appropriate major element (20) and trace element chemistry to provide MORB.

In order to see if this holds up quantitatively for the trace elements we investigate the following model. The primitive mantle is split into two reservoirs by partial melting and melt extraction. We use partition coefficients appropriate for a peridotite residue (3,6). These two reservoirs are the melt fraction, which we take as 15% of the whole mantle, and the depleted residual crystals. The melt fraction reservoir is enriched in the incompatible trace elements but, because of the small partition coefficients, has nearly primitive ratios of Rb/Sr and Sm/Nd. It therefore evolves in a manner similar to undepleted mantle. During crystallization of the melt, garnet settles and volatiles rise. Garnet is the liquidus phase in eclogite at pressures greater than 30 kb (16) and garnet and clinopyroxene are the liquidus phases between 21 and 30 kb. We construct the proto-MORB source region by taking a 50:50 mix of the melt and garnet crystals which are in equilibrium with it. Below about 50 km this assemblage will crystallize as eclogite which is denser than the melt and the residual crystals from the primary differentiation. To simulate volatile redistribution, or mantle metasomatism, we extract 50 percent of the final 5% melt fraction and infiltrate the overlying depleted residue. For this we use partition coefficients appropriate for an eclogite residue. This newly enriched source region is assumed to be composed of 10% of this late stage melt and 90% residual crystals. The boundary condition that leads to the partial melt fraction and the mixing ratios is that the enriched source region can provide continental tholeiites by 20 percent melting.

Results of this model are shown as solid points in Figure 2. They are consistent with MORB being the result of nearly complete melting of a source region which evolved from the melt fraction of the primary differentiation. This, of course, will crystallize as an eclogite assemblage.

Prior to providing depleted MORB this region lost its late stage fluids or, alternatively, crystallized completely and then lost its early melt fraction on a subsequent reheating cycle. PLUME was enriched by upward migration of this fluid. Thus, two stages of differentation and fractionation are required in order to concentrate the LIL in the two upper mantle reservoirs. The MORB source evolves as nearly primitive mantle until it transfers its incompatible elements to PLUME.

Basalts from PLUME will have time-integrated depleted, enriched or "primitive" isotopic ratios, depending on when the enrichment occurred.

Locations of the two source regions

There is variety of evidence that suggests that the plume source region is shallow. Anomalously low seismic velocities can be traced to a depth of about 250 km under Yellowstone but deeper velocities appear to be normal (17). The variable and small amounts of partial melting required to generate melilitites, nephelenites, basanites and alkali basalts (6) from a common source region are consistent with diapirs rising from various shallow depths. Tholeiites are the result of larger degrees of melting, consistent with adiabatic ascent from deeper levels. The xenoliths entrained in kimberlites and alkali basalts are volatile and trace element rich and these are samples from the upper 200 km of the mantle. Intuitively, we expect that volatiles will migrate upward and be trapped by the cold upper mantle. Volatile and LIL enriched magmas occur not only under continents but also at island arcs where the downgoing slab perturbs the upper mantle. Plume type basalts occur in continental rifts which are replaced by oceanic ridges, with isolated oceanic island hotspots, when the rifting has led to the formation of an ocean basin.

There are also some suggestive geometric constraints. The volume of the low-velocity zone (LVZ) is adequate to provide the plume basalts but not the voluminous MORB (10). The preferred mode of convection in a region with a high temperature gradient and a rapidly varying viscosity is hexagonal cells with upwelling centers (18). This seems to be consistent with hotspot patterns (19) and the small areal extent of hotspots. In more homogeneous regions of the mantle, where the temperature gradient is smaller and the viscosity more uniform, linear rolls are a possible mode of heat transport. Linear ridge systems and the uniformity of oceanic tholeiites therefore suggest a deeper source, one that is below the large vertical and lateral variations that occur in the upper 200 km. The sink of oceanic lithosphere appears to be between 200 km and 670 km. The distinctive isotopic and trace element signature of MORB can be maintained if its source region is also between these depths. Upper mantle temperatures are closest to the melting point between about 150 and 250 km depth and this is therefore the depth range where it is most likely for diapirs to originate.

It is difficult to estimate the depth at which partial melting first occurs. Seismic data from several hotspots give low-velocities down to at least 150 km (17,21). Eruption temperatures of 1300°C and large degrees of partial melting require initiation of melting below 150-200 km (22). There is some evidence for crystal fractionation in melts as deep as 280 km (23). Mantle fragments brought up by alkali basalts and kimberlites do not, in general, have the trace element pattern required for the source region of MORB. Therefore, PLUME magmas may originate from shallow depths but the MORB source must be deeper. In a gravitationally stratified mantle one would expect the deeper layer to be denser and therefore rich in garnet. The inability of young buoyant lithosphere to subduct below about 220 km suggests a density increase at this depth and this may be the boundary between the two source regions. Taking all evidence into account it appears that PLUME may be coincident with the LVZ and diapirs rising from the transition region supply the magmas that evolve to MORB.

Isotopic ratios

The study of Sr and Nd isotopes has placed constraints on the evolution of mantle reservoirs (24, 25, 26). The continental crust and the depleted reservoir have mean ages of 1.5 b.y. (3). Kimberlites and continental flood basalts, although enriched in LIL, have been attributed to a primitive reservoir (22, 27). Some mantle samples have been derived from ancient enriched reservoirs (28). Other samples come from reservoirs which apparently have been enriched only recently (29). The measure of enrichment or depletion is ε which is the $^{143}Nd/^{144}Nd$ or $^{87}Sr/^{86}Sr$ ratio of the basalt relative to the ε value for undifferentiated mantle times 10^4 (24). Some PLUME magmas have ε values near zero and have been thought to come from a primitive, undifferentiated, deep mantle reservoir (24). This interpretation is not required by the data.

Consider a primitive mantle that partially melts and separates into two reservoirs, as before, by upward removal of the melt. The lower mantle consists of residual crystals and is therefore depleted in the incompatible elements. The upper left quadrant of Fig. 2 gives the ε values for the depleted mantle for various times of separation and for two degrees of partial melting. Large ε values develop for early separation of the two reservoirs. Magmas separating from this reservoir will have a depleted isotopic signature. The melt fraction of the original differentiation is shown in the lower right hand quadrant. Note that for 20% melting the enriched reservoir is very close to the origin, i.e. "primitive", even for separation as early as 3 AE. This is a consequence of the low partition coefficients.

Although the incompatible elements are transferred to the upper mantle in the magma they do not necessarily remain in that fraction. The melt crystallizes as oceanic crust and, at higher pressures, an upper mantle eclogite layer. As the magma solidifies, or upon subduction and later remelting, the volatiles and the incompatible trace elements enter and are trapped by the colder part of the upper mantle, continental crust and lithosphere.

To model this we assume that some of the melt fraction resulting from the original differentiation crystallizes in the upper mantle as a garnet and clinopyroxene rich solid. To simulate volatile redistribution by LIL rich fluids, such as kimberlites or alkali basalts, we extract 5% melt and mix this with the overlying mantle which initially had concentrations calculated for the residual phase from the earlier melting event. The invaded mantle is assumed to contain 10 weight percent of this melt. These proportions lead to a composition that approximates the composition of the continental tholeiite source region but are otherwise selected just for purpose of illustration. The relations of this enriched source region and the complementary newly depleted region are shown in Figure 3 as enriched residue and "depleted melt". Note that the enriched and depleted reservoirs change roles by the transfer of only a small amount of material. This is a consequence of the small partition coefficients and the efficient concentration of trace elements into the fluid. In this model, mid-ocean ridge basalts are derived from a reservoir which was the partial melt fraction of the original mantle separation. It lost most of its volatiles and LIL either in the course of crystallizing or by a later partial melting/degassing event precursory to the melting which presently provides MORB. The region receiving these volatiles was part of the refractory residue of the original differentiation and is now the hotspot source region.

In the calculations the original differentiation and the subsequent removal of volatiles from the melt were assumed to occur at the same time. If the redistribution is delayed, the MORB source region will evolve as a slightly enriched reservoir until the volatile extraction occurs. It will subsequently evolve as a depleted reservoir. This reduces the range of the variations since, in effect, it results in a mixture of the two source regions. A redistribution of LIL makes it possible to satisfy the mantle isotopic data even if the primary differentiation occurred early in the history of the Earth.

By adjusting the timing of the differentiation events the "enriched" reservoir can be made to have arbitrary small ε values. Thus the trace element, petrological and thermal constraints on the evolution of the mantle and the various reservoirs are not contradicted by the isotopic data. The type of model investigated here is similar to previous ideas of mantle metasomatism and trace element redistribution

(30).

Implications for mantle evolution

Isotopic studies indicate that the two major mantle reservoirs have been isolated for more than 1 or 2 b.y. (2,3). The evidence presented here from trace elements, and previously from major element and seismic considerations (20), indicate that the mantle is chemically stratified and that the various regions of the mantle are complementary products of terrestrial differentiation. The present emphasis has been on magmas from these reservoirs but similar conclusions result from the study of solid fragments from the mantle (14, 20). O'Hara et al. (14) pointed out that the restricted number of phases found in bimineralic eclogites from kimberlites indicate that they are either crystal accumulates or crystalline residue developed in contact with a liquid. This is exactly the situation inferred from the trace element patterns for the source region of abyssal tholeiites. Eclogite and garnet peridotite xenoliths from kimberlites may represent samples from MORBS and PLUME, respectively. They give satisfactory average mantle compositions for the major oxides when combined in the portions indicated by the trace elements (20).

Although whole mantle convection, in the conventional sense, is precluded in a chemically stratified mantle, transfer of material into and out of the various reservoirs is possible because of the large volume change associated with partial melting and phase changes, e.g., basalt-eclogite. The oceanic part of the plate tectonic cycle may be summarized as follows. Partial melting in the eclogite layer allows diapirs to rise to the base of the oceanic lithosphere. Nearly complete melting occurs during adiabatic ascent. This is possible because of the proximity of the liquidus to the solidus in eclogite and the increase in pressure associated with the melting process. The resulting melt fractionates in near surface magma chambers to form tholeiitic melts which are light enough to rise to the surface. The denser residue forms the lower oceanic lithosphere. As the lithosphere cools it becomes unstable and returns to its source region. Partial melting in the shallow enriched peridotite layer generates continental and ocean island basalts and a harzburgite residue, both of which are lighter than their source region. These PLUME products remain in the crust and upper mantle. Some volatiles are returned to PLUME by subducted sediments and hydrothermally altered oceanic crust.

It has generally been assumed that basalts of all kinds represent partial melts of peridotites. Estimates of mantle composition based on this premise have much lower abundances of SiO_2, Al_2O_3, and CaO than models based on cosmochemical considerations. The evidence used to construct the petrological models is mostly obtained from the upper 200 km of the mantle and the models are therefore strictly only valid for the upper mantle. A thick eclogite layer serves to increase the abundances of the above components and can reconcile the cosmochemical and petrological interpretations.

The idea that eclogite may be the source for oceanic basalts is an old one (31) but has not been in favor in recent years. The main objection is that limited partial melting of eclogite does not generate a tholeiite. Extensive or complete melting is required and this has been thought to be unlikely.

However, eclogite has an extremely small melting interval (about 60°C) compared to peridotite (16,32). Since diapirs cannot rise out of an eclogite layer into a less dense peridotite layer until they are already extensively molten, it requires only a small additional temperature rise, relative to the liquidus, to complete the melting. This can be accomplished in a rising diapir. It is still unknown what initiates melting in the first place.

The locations of hotspots and ridges in the Atlantic and Indian oceans are such that there were beneath continental lithosphere prior to 200 m.y. ago and were insulated by continents for at least another 150 m.y. before that. This suggests that continental insulation, which prevents mantle heat from being efficiently removed to the surface, may be the cause of the partial melting that ultimately results in ridge and hotspot volcanism. The thick, 150 km, continental lithosphere (20) prevents diapiric uprise and extensive melting may be possible until the continent rifts and rapid spreading and heat removal can take place. It is not so obvious that this explanation holds for the ridges and hotspots in the Pacific. The thick crust under the oceanic plateaus in the central Pacific or a thick oceanic lithosphere, due to a period of slow spreading, could also serve to insulate the mantle, raise temperatures and cause extensive in situ melting prior to diapiric ascent.

There is an additional source of heating associated with deep melting that has been overlooked. Partial melting involves a volume increase that cannot be completely accommodated by flow in the adjacent mantle or uplift. This raises the pressure in the melt which leads to a further temperature increase and more melting (32). This plus shear heating may make melting a runaway process (33).

Summary

Garnet and possibly clinopyroxene control the complementary trace element patterns of MORB and plume basalts. This suggests that the source region for MORB was formed by crystallization at depth of the melt fraction of the original differentiation of the Earth. The plume source is enriched in those elements that are concentrated in a fluid phase that was removed from a garnet rich region. This fluid, the result of an early partial melt or a late stage fluid from crystallizing eclogite, infiltrated the shallow mantle. This gives plume basalts an inverse garnet trace element signature. The MORB and plume source regions together make up about 25-30% of the mantle. There is no need to invoke a large primitive reservoir in the mantle or deep, lower mantle plume sources. On the contrary, the plume source region appears to be shallow and may be coincident with the LVZ. The upper mantle transition region, 220-670 km, represents about 21% of the mantle and the LVZ is about one-third as large. This is about the ratio of the sizes of the two upper mantle reservoirs which is required to satisfy the trace element data.

References and Notes

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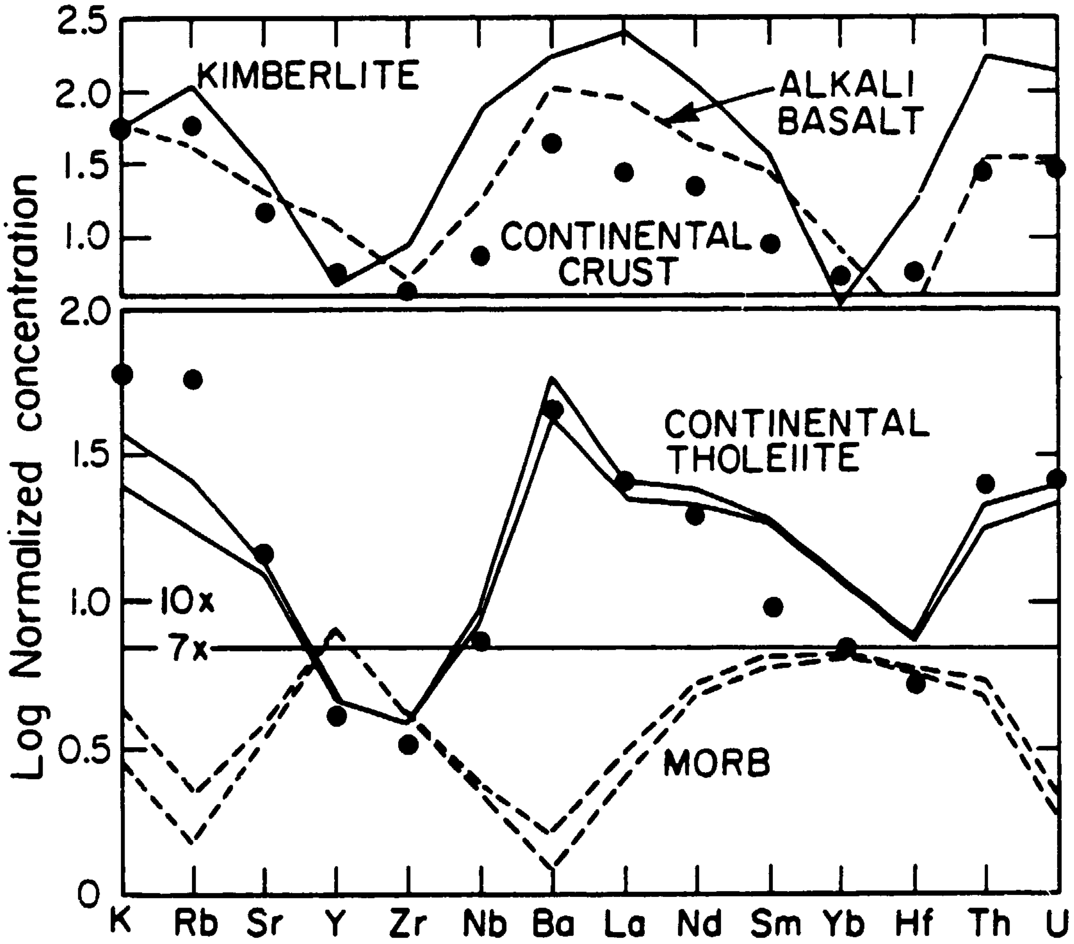
Figure Captions

Figure 1 Trace element concentrations in the continental crust (dots) and mid-ocean ridge basalts (8, 34, 36). All concentrations are normalized to terrestrial values of Ganapathy and Anders (37), recalculated to mantle equivalents. The lower curves for continental tholeiites and MORB are normalized to mantle concentrations after removal of the continental crust, as are the curves for alkali basalts and kimberlites. A near terrestrial pattern for the very incompatible elements can be obtained by mixing continental tholeiites and MORB giving an enrichment of the combined magma types of about 7 times the original mantle concentrations.

Figure 2 Crystal/liquid partition coefficients for garnet, clinopyroxene, orthopyroxene and olivine (6). Heavy line is ratio of concentrations in primitive mid-ocean ridge basalts (36) and continental tholeiites (2,6). This indicates that MORB results from melting of garnet and clinopyroxene but the continental tholeiite (CFB) source region has experienced eclogite extraction. The points are for a model in which the MORB source region is the initial melt fraction from a primitive reservoir plus garnet cumulates and the continental basalt, or plume, source region, is the original depleted residue enriched by a late stage melt from the proto-MORB source.

Figure 3 The present day $\varepsilon_{Nd}-\varepsilon_{Sr}$ values for a primitive mantle split into an enriched and a depleted reservoir by partial melting at the time indicated. The solid triangles are for a model in which the initially enriched reservoir transfers its final 5% melt fraction to the originally depleted reservoir, forming an "enriched residue." The original differentiation and the depletion-enrichment event are assummed to occur simultaneously. Partition coefficients from ref. 6 were used in the calculation.


2.5
2.0
1.5
1.0
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ALKALI
BASALT
CONTINENTAL
CRUST
2.0
1.5
1.0
0.5
0
10x
7x
CONTINENTAL
THOLEIITE
MORB
Log Normalized concentration
K
Rb
Sr
Y
Zr
Nb
Ba
La
Nd
Sm
Yb
Hf
Th
U

Fig. 1

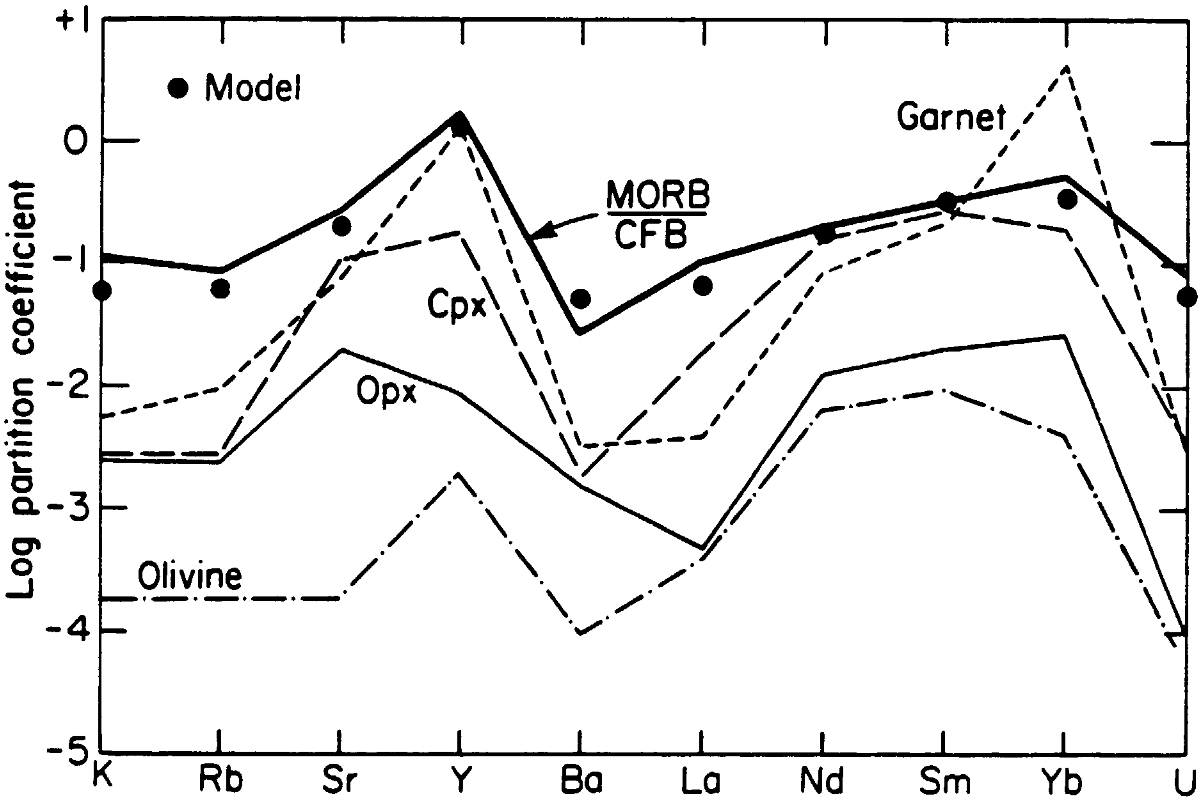
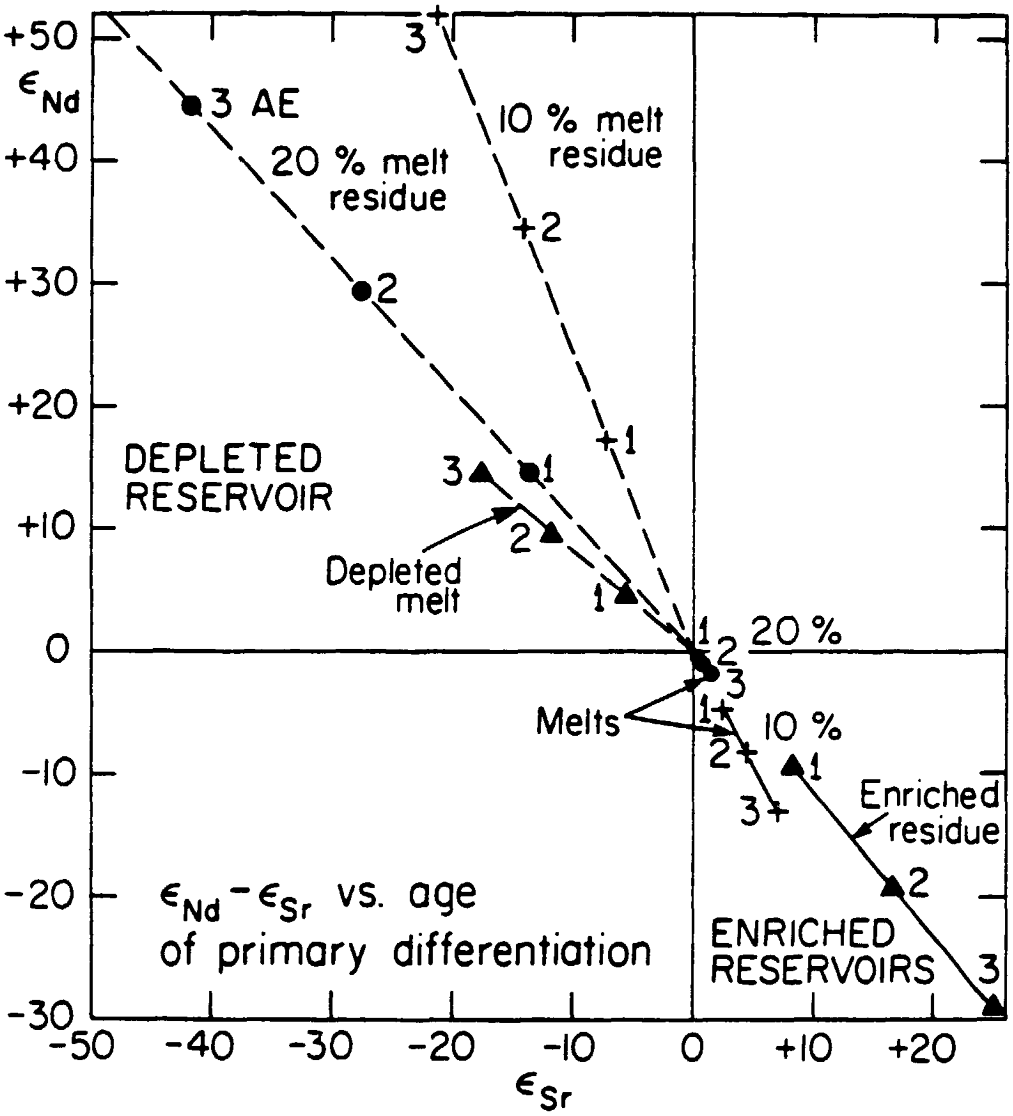

● Model
Garnet
MORB
CFB
Cpx
Opx
Olivine
Log partition coefficient
+1
0
-1
-2
-3
-4
-5
K
Rb
Sr
Y
Ba
La
Nd
Sm
Yb
U

Fig. 2



+50
+40
+30
+20
+10
0
-10
-20
-30
ϵ_{Nd}
-50
-40
-30
-20
-10
0
+10
+20
ϵ_{Sr}
3 AE
20 % melt
residue
10 % melt
residue
3
2
1
DEPLETED
RESERVOIR
Depleted
melt
20 %
10 %
Melts
Enriched
residue
ENRICHED
RESERVOIRS
$\epsilon_{Nd}-\epsilon_{Sr}$ vs. age
of primary differentiation

Fig. 3